ATOMIC DATA AND NUCLEAR DATA TABLES **70,** 119–134 (1998)
ARTICLE NO. DT980788

BREIT–PAULI ENERGIES, TRANSITION PROBABILITIES, AND LIFETIMES FOR $2s$, $2p$, $3s$, $3p$, $3d$, $4s$ ^2L LEVELS OF THE LITHIUM SEQUENCE, $Z = 3–8$

C. FROESE FISCHER and M. SAPAROV

Computer Science Department, Vanderbilt University
Nashville, Tennessee 37235

G. GAIGALAS

Institute of Theoretical Physics and Astronomy
A. Goštauto 12, 2600 Vilnius, Lithuania

and

M. GODEFROID

Belgian National Fund for Scientific Research (FNRS)
Laboratoire de Chimie Physique Moléculaire, CP160/09, Université Libre de Bruxelles
50 av. F.D. Roosevelt, B 1050 Brussels, Belgium

Multiconfiguration Breit–Pauli energy levels, lifetimes, and transition data are presented for the lithium sequence in the range $Z \leq 8$. Included are all J-levels of the six lowest ^2L terms, namely those with configuration labels $1s^22s$, $1s^22p$, $1s^23s$, $1s^23p$, $1s^23d$, and $1s^24s$. © 1998 Academic Press

0092-640X/98 $25.00

CONTENTS

INTRODUCTION

With the aid of powerful workstations and systematic methods, a considerable improvement in accuracy has been achieved in the calculation of nonrelativistic transition data for light atoms using the multiconfiguration Hartree–Fock (MCHF) method (see [1] for a review). Accuracy criteria for such calculations are agreement in length and velocity form of the line strength or oscillator strength along with a simultaneous close agreement with the observed transition energy. For the $2s^2 2p\ ^2P^o$–$2s2p^2\ ^2D$ transition in B I, for example, the length and velocity gf-values differed by less than 0.4% when the nonrelativistic transition energy differed from the observed by about 0.1% [2]. Besides neglecting the finite nuclear mass and relativistic effects, most of these calculations have been benchmark calculations of isolated resonance transitions.

In this paper we report results of Breit–Pauli calculations for a portion of a spectrum of lithium and lithium-like ions with nuclear charge $Z \leq 8$. Included are the energies of all J-levels of the six lowest $2s$, $2p$, $3s$, $3p$, $3d$, $4s\ ^2L$ terms and all allowed transitions between the levels of these terms. From the latter, the lifetime of each level can be computed, the quantity measured in experimental techniques relying on the analysis of decay curves. For some transitions, lifetimes immediately provide transition rates, but for excited states a knowledge of branching ratios is needed before measured lifetimes can yield transition rates. Thus, theoretical calculations for excited states play a valuable role in spectroscopy.

The computational method used in this work follows standard procedures [3] and nonrelativistic results for several atomic properties will be described elsewhere [4]. Briefly, the wave function $\Psi(\gamma LS)$ for an atomic state labeled by the configuration γ, and the term LS is approximated by a linear combination of configuration state functions (CSFs),

$$\Psi = \sum_{i=1}^{M} c_i \Phi(\gamma_i LS). \tag{1}$$

Each $\Phi(\gamma_i LS)$ is constructed from one-electron spin orbitals for the configuration γ_i and is of the same LS symmetry as the atomic state function. In the MCHF method, the radial functions used to construct the CSFs and the expansion coefficients c_i are determined variationally so as to leave the nonrelativistic energy stationary with respect to variations in the radial functions and the expansion coefficients [3]. Once radial functions have been determined, a configuration interaction calculation can be performed over the set of configuration states, where the interaction matrix is evaluated with respect to the Breit–Pauli (BP) Hamiltonian and, since the elements in this work are light elements, the specific mass-shift operator was included as well in the Hamiltonian. New, efficient programs based on the combination of second quantization in coupled tensorial form, and a generalized graphical technique [5] were used for performing angular integrations for the evaluation of matrix elements.

The configuration states included in the expansions of the different terms were obtained by including all possible CSFs of a given LS symmetry that could be constructed from orbitals with $n \leq 10$, $l \leq 7$ (k orbitals), and with at least one orbital in the configuration with $n \leq 4$. The largest expansion for this rule-based scheme was for ^2D, where the interaction matrix size was 15,606. A distributed version of the Breit–Pauli code using a message passing interface (MPI) was used to generate the interaction matrix and obtain selected eigenvalues and

TABLE A
Comparison of Observed and Computed Breit–Pauli Excitation Energies in cm^{-1} as a Function of Z, Along with the Difference, Observed Minus Computed

Level \ Z =		3	4	5	6	7	8
$2p$	$^2P^o_{1/2}$						
	Exp.	14903.6481	31928.76	48358.40	64483.8	80463.2	96375.0
	MCHF	14904.1089	31932.27	48367.61	64503.2	80500.2	96441.0
	Diff.	-0.4608	-3.51	-9.21	-19.4	-37.0	-66.0
$2p$	$^2P^o_{3/2}$						
	Exp.	14903.9835	31935.34	48392.50	64591.0	80721.9	96907.5
	MCHF	14904.4423	31938.82	48401.64	64610.3	80759.1	96972.8
	Diff	-0.4588	-3.48	-9.14	-19.3	-37.2	-65.3
$3s$	$^2S_{1/2}$						
	Exp.	27206.0952	88231.91	180202.09	302847.8	456126.6	640039.8
	MCHF	27203.9689	88230.45	180203.33	302861.4	456165.5	640126.5
	Diff.	2.1263	1.46	-1.24	-13.6	-38.9	-86.7
$3p$	$^2P^o_{1/2}$						
	Exp.	30925.5530	96495.36	192951.40	320048.9	477765.7	666113.2
	MCHF	30924.0285	96494.71	192952.65	320061.6	477792.3	666169.4
	Diff.	1.5245	0.65	-1.25	-12.7	-26.6	-56.2
$3p$	$^2P^o_{3/2}$						
	Exp.	30925.6494	96497.28	192961.42	320080.4	477842.0	666269.8
	MCHF	30924.1241	96496.64	192962.69	320093.1	477867.6	666324.5
	Diff.	1.5253	0.64	-1.27	-12.7	-25.6	-54.7
$3d$	$^2D_{3/2}$						
	Exp.	31283.0505	98054.57	196068.89	324878.5	484404.3	674625.7
	MCHF	31280.5311	98052.61	196067.89	324882.3	484407.0	674632.9
	Diff.	2.5194	1.96	1.00	-3.8	-2.7	-7.2
$3d$	$^2D_{5/2}$						
	Exp.	31283.0866	98055.12	196071.81	324887.7	484426.3	674676.8
	MCHF	31280.5671	98053.19	196070.81	324891.5	484429.5	674679.5
	Diff.	2.5195	1.93	1.00	-3.8	-3.2	-2.7
$4s$	$^2S_{1/2}$						
	Exp.	35011.5432	115464.40	237698.45	401346.6	606348.8	852696.
	MCHF	35009.2270	115461.45	237695.60	401352.1	606363.3	852736.8
	Diff.	2.3162	2.95	2.85	-5.5	-14.5	-40.8

Note. For lithium, observed values are from [11], for beryllium from [12], for boron from [13], for carbon from [14], and for nitrogen and oxygen from the NIST publication [15].

eigenvectors [6]. Once the eigenvectors were determined, a nonorthogonal version of the transition code was used to compute transition data [7].

Calculations of relativistic radiative transition probabilities rely on gauge invariance and generally use either the Coulomb or Babushkin gauge [8]. The nonrelativistic limit of the former is the velocity form, whereas the latter is the length form. In the MCHF + BP approach, the relativistic corrections are included in the description of the wave function. With such wave functions, no correction to the length form formula of the dipole matrix element is needed [9], but corrections are needed for the nonrelativistic veloc-

TABLE B
Comparison of the Fine-Structure Separation (in cm^{-1}) with Other Theory (FCPC [18], HR [17]) and Experiment

Term	Method \ $Z =$	3	4	5	6	7	8
$2p\ ^2P$	MCHF	0.3334	6.5542	34.032	107.085	258.919	531.76
	FCPC	0.3333	6.5569	34.038	107.06	258.74	530.94
	HR	0.335273					
	Exp.	0.3353	6.58	34.10	107.2	258.7	532.5
$3p\ ^2P$	MCHF	0.0957	1.9280	10.045	31.529	75.275	155.07
	FCPC	0.0954	1.9263	10.019	31.519	76.180	156.37
	Exp.	0.0964	1.92	10.02	31.5	76.3	156.6
$3d\ ^2D$	MCHF	0.0360	0.5759	2.913	9.206	22.480	46.629
	Exp.	0.0361	0.55	2.92	9.2	22.0	51.1

Note. For lithium, observed values are from [11], for beryllium from [12], for boron from [13], for carbon from [14], and nitrogen and oxygen from the NIST publication [15].

ity form. Rudzikas et al. [10] have derived velocity form expressions for the intercombination transitions, retaining only corrections that contain the spin operator in the expansion. To our knowledge, these expressions have not been applied to multiconfiguration wave function expansions. Thus, in working with Breit–Pauli approximations, it is customary to report results only in the length form and use energy criteria, such as fine-structure splitting, to evaluate the accuracy of the Breit–Pauli approximation.

Table A shows the energy levels in cm^{-1} relative to the ground state for part of the lithium sequence with $Z \leq 8$, comparing observed and computed energies, and their difference, observed minus computed. If we assume the observed energy levels are accurate, this difference represents the error in our approximation. For lithium, the observed energy levels were from the very accurate tabulations reported by Radziemski et al. [11], for beryllium from [12], for boron from [13], for carbon from [14], and all others from the NIST tabulations [15]. The differences with observed energies range from a few cm^{-1} for lithium to as many as 87 cm^{-1} for oxygen ($Z = 8$). Not included in this work were the QED effects which are particularly important for the $2s\ ^2S$ ground states. In the case of O^{+5}, Chung [16] reports a QED correction which would add 29.5 cm^{-1} to the

TABLE C
Comparison of Present Decay Rates for $2p\ ^2P^o$ States of the Lithium Sequence (in Units of $10^8\ s^{-1}$) with HR [21] and RMBPT [23] Values

Method \ $Z =$	3	4	5	6	7	8
$2p\ ^2P^o_{1/2}$ - $2s\ ^2S_{1/2}$						
MCHF	0.368960	1.12958	1.89069	2.63205	3.36234	4.08832
MCHF[a]	0.368926	1.12923	1.88961	2.62970	3.35771	4.07993
HR	0.36894(2)	1.1289(1)	1.8886(1)	2.6281(1)	3.3556(2)	4.0764(2)
RMBPT	0.3690	1.129	1.889	2.630	3.357	4.078
$2p\ ^2P^o_{3/2}$ - $2s\ ^2S_{1/2}$						
MCHF	0.368986	1.13032	1.89494	2.64592	3.39648	4.15928
MCHF[a]	0.368952	1.12998	1.89387	2.64364	3.39179	4.15088
HR	0.36896(2)	1.1297(1)	1.8932(1)	2.6425(1)	3.3905(2)	4.1487(2)
RMBPT	0.3690	1.130	1.894	2.644	3.392	4.150

[a] Normalized to the observed transition energy.

TABLE D
Comparison of Present Decay Rates for $3s\ ^2S$ to $2p\ ^2P^o$ States of the Lithium Sequence (in Units of $10^9\ s^{-1}$) with RMBPT [23] Values

Method \ $Z =$	3	4	5	6	7	8
$3s\ ^2S_{1/2}$ - $2p\ ^2P^o_{1/2}$						
MCHF	0.011154	0.13609	0.53744	1.4188	3.0354	5.6952
RMBPT	0.01114	0.1359	0.5367	1.418	3.032	5.680
$3s\ ^2S_{1/2}$ - $2p\ ^2P^o_{3/2}$						
MCHF	0.022306	0.27212	1.0745	2.8365	6.0679	11.386
RMBPT	0.02228	0.2719	1.074	2.840	6.073	11.39

differences between observed and computed, reducing the error by about a factor of two, except in the case of $3d\ ^2D$. The results reported here are entirely *ab initio:* there has been no extrapolation with respect to the basis or the angular quantum number in the nonrelativistic wave function. The errors reported in Table A represent an imbalance in the correlation included in the individual calculations (particularly the correlation in the core), and an incomplete representation of the relativistic shift and other Breit–Pauli operators computed from a basis optimized for the nonrelativistic Hamiltonian. For the $^2P^o$ and ^2D states the difference in the errors for the two *J*-levels is the discrepancy between theory and observation in the fine-structure splitting.

Table B analyzes the fine-structure splitting more carefully. For the $2p\ ^2P^o_{1/2,3/2}$ state, a very accurate calculation has been reported by Yan and Drake [17] in perfect agreement with experiment for lithium. We also compare the present results with full-core-plus-correlation (FCPC) results obtained by Wang et al. [18] that include a small QED correction, increasing the splitting. Thus our uncorrected results should be smaller than the observed ones which is not the case for N V ($Z = 7$). For $3p$ of B^{+2}, our splitting is too large by 0.025 cm^{-1} or 0.25%. The fine-structure splitting for $3d$ is also reported. Differences with observation are now more variable and may be due to uncertainty in the experimental value.

The $2s$–$2p$ transition in lithium has been determined to high precision by Yan and Drake [19], whose paper contains an extensive review of the literature for this transition. Using a Hylleraas expansion, correlation and finite nuclear mass are treated to high accuracy. When a small relativistic correction is included, their results are in excellent agreement with the most accurate experiment by McAlexander et al. [20]. Recently their work has been extended to the isoelectronic sequence [21] and compared with earlier work by Chung [22]. Agreement between the two theories is excellent (within a few units in the last place reported by Chung) though the Yan et al. [21] nonrelativistic *f*-values have been determined to about nine significant digits. In order to correct these for relativistic effects, they rely on relativistic many-body perturbation theory (RMBPT) tabulations [23] believed not to be sufficiently accurate for low *Z* because of an incomplete treatment of correlation. In Table C we compare the present Breit–Pauli transition or decay rates for the $2p\ ^2P^o_{1/2}$ and $2p\ ^2P^o_{3/2}$ levels.

The accuracy of the present methodology can be assessed from this extensively studied transition. In Table C, six digits are quoted in order to show the difference between our results and those of Hylleraas (HR) and RMBPT. For low *Z*, given the nature of the three methods, it is difficult to say with certainty which is the definitive value. The experimental measurement [20] for $2p\ ^2P^o_{1/2}$, converted to a decay rate, is $0.368976(95) \times 10^8\ s^{-1}$, a result in agreement with all three methodologies. For $3s\ ^2S_{1/2}$ our lifetime of 29.886 ns is in excellent agreement with a value of 29.84(7) ns obtained from beam gas laser spectroscopy [24]. For higher *Z*, the present decay rates are affected by the neglect of QED corrections. Because the rate depends on the ΔE^3, any error in the theoretical transition energy is magnified. Transition energies can often be measured accurately. In such cases, theoretical results can be *normalized* to the observed transition energy, yielding the most reliable transition rates. Such normalized values are also shown in Table C and agree closely with RMBPT values (which likewise had been normalized to observed transition energies). Included with the HR values is an estimate of uncertainty: from the agreement between the MCHF normalized results and RMBPT, it would appear that some of these estimates are on the low side. As shown in Table D, the present decay rates from $3s\ ^2S_{1/2}$ to the $2p\ ^2P^o_{1/2}$ and $2p\ ^2P^o_{3/2}$ levels also are in excellent agreement with similar quantities reported by Johnson et al. [23]. For the $3d\ ^2D$ of lithium, the dependence on *J* is extremely small and

TABLE E
Estimated Error on the Line Strength in Parts per Thousand

Transition \ $Z =$	3	4	5	6	7	8
$2s-2p$	0.26	0.20	0.22	0.29	0.34	0.32
$2p-3s$	0.76	0.85	0.80	0.60	0.53	0.55
$2s-3p$	3.27	0.48	0.20	0.27	0.34	0.43
$3s-3p$	0.61	0.70	0.71	0.65	0.59	0.61
$2p-3d$	0.09	0.15	0.22	0.32	0.36	0.44
$3p-3d$	3.06	2.85	3.55	3.44	3.29	3.00
$2p-4s$	1.29	1.46	1.22	0.85	0.71	0.66
$3p-4s$	0.60	0.19	0.16	0.25	0.32	0.42

our lifetimes of 14.591 and 14.592 ns for $^2D_{3/2}$ and $^2D_{5/2}$, respectively, again are in perfect agreement with the value of 14.589(14) ns [24] obtained by the same experimental method.

The accuracy of computed transition data depends on both the accuracy of the transition energy and the accuracy of the line strength. The accuracy of the former is best determined from experiment, where often (though not always!) more reliable values can be obtained. The sensitivity of the line strength to cancellations in the calculation of the one-electron radial dipole matrix element and correlation can be assessed through a comparison of the deviation from unity of the ratio of the length (independent of transition energy) and velocity (dependent on transition energy) matrix elements in the nonrelativistic limit. The most stable line strength is for the 2*p*–3*d* transition where both radial functions have the same sign so that there is no cancellation in the one-electron dipole matrix element. At the same time, the transition energy is sufficiently large that it can be computed to a relatively high accuracy fairly readily. On the other hand, the 3*s*–3*p* one-electron radial dipole matrix element is sensitive to cancellation and the transition energy, being small, cannot be computed to a high accuracy, manifesting itself in a relatively large discrepancy in the length (S_l) and velocity (S_v) form of the line strength obtained from nonrelativistic wave functions. Thus we propose to use the deviation from unity of S_l/S_v as a measure of the uncertainty in the line strength. To this needs to be added some uncertainty due to relativistic corrections. In this particular study, the relativistic effects on the line strength are small, in fact less than 2% for the highest ion, O^{+5}. Assuming that these effects themselves are captured accurately to within 2% in our methodology, the result is an uncertainly of 0.4 parts per thousand for $Z = 8$. In Table E, we present a table of $1000 \times |S_l/S_v - 1| + (Z/8)^2 \times 0.4$ to represent the uncertainty in units of parts per thousand in the line strength.

In this paper we present similar data for the six terms and dipole transitions between these terms, for $Z = 3$ to $Z = 8$. Table I contains energy level information, the fine structure splitting, and the lifetimes computed from the allowed E1 transitions. These values are similar to the nonrelativistic values reported by Chung [22], but show the relativistic effect. Table II reports the transition energy, line strength (in length form), oscillator strength, and transition rate. All Tables were computer generated, and lifetimes and transition rates have not been further normalized to agree with the observed energy.

Acknowledgments

M.G. thanks the Belgian National Fund for Scientific Research (FRFC Conventions 2.4533.91 and 2.4551.92) and the French Community of Belgium (Research Convention ARC-93/98-166) for financial support. This research was supported in part by the Division of Chemical Sciences, Office of Basic Energy Sciences, Office of Energy Science, U.S. Department of Energy. The revised Breit–Pauli program was developed as part of a cooperative research project funded by the National Science Foundation under Grant PHY-9501830. The Breit–Pauli calculations, including orbit–orbit interactions which double the CPU time required, were performed on the CrayT3E at the National Energy Research Scientific Computing Center at Lawrence Berkeley Laboratory, supported by the U.S. Department of Energy.

References

1. M. R. Godefroid, C. Froese Fischer, and P. Jönsson, Phys. Scripta T **65,** 70 (1996)

2. P. Jönsson, C. Froese Fischer, and M. Godefroid, J. Phys. B **29,** 2393 (1996)

3. C. Froese Fischer, T. Brage, and P. Jönsson, *Computational Atomic Structure* (IOP, Bristol, 1997)

4. M. Godefroid, C. Froese Fischer, and P. Jönsson, in preparation

5. G. Gaigalas, Z. Rudzikas, and C. Froese Fischer, J. Phys. B **30,** 3747 (1997)

6. M. Saparov and C. Froese Fischer, "An MPI Implementation of the MCHF Atomic Structure Package," U.S. Department of Energy Technical Report DOE/ER/14761-1

7. J. Olsen, M. R. Godefroid, P. Jönsson, P. Å. Malmqvist, and C. Froese Fischer, Phys. Rev. E **52,** 4499 (1995)

8. I. P. Grant, J. Phys. B **7,** 1458 (1974)

9. G. W. F. Drake, Phys. Rev. A **5,** 1979 (1972)

10. Z. B. Rudzikas, J. M. Kaniauskas, G. V. Merkelis, and E. H. Savicius, J. Phys. B **16,** 2879 (1983)

11. L. J. Radziemski, R. Engleman, Jr., and J. W. Brault, Phys. Rev. A **52,** 4462 (1995)

12. L. Johansson, Ark. Fys. **20,** 489 (1961)

13. A. Ölme, Ark. Fys. **40,** 35 (1969)

14. M. Tunklev, L. Engström, C. Jupén, and I. Kink, Phys. Scripta **55,** 707 (1997)

15. W. L. Wiese, J. R. Fuhr, and T. M. Deters, *Atomic Transition Probabilities of Carbon, Nitrogen, and Oxygen*, J. Chem. Phys. Ref. Data, Monograph 7 (AIP, New York, 1996)

16. K. T. Chung, Phys. Rev. A **45,** 7766 (1992)

17. Z.-C. Yan and G. W. F. Drake, Phys. Rev. Lett. **79,** 1646 (1998)

18. Z.-W. Wang, X.-W. Zhu, and K. T. Chung, Phys. Scripta **47,** 65 (1993)

19. Z.-C. Yan and G. W. F. Drake, Phys. Rev. A **52,** R4316 (1995)

20. W. I. McAlexander, E. R. I. Abraham, and R. G. Hulet, Phys. Rev. A **54,** R5 (1996)

21. Z.-C. Yan, M. Tambasco, and G. W. F. Drake, Phys. Rev. A **57,** 1652 (1998)

22. K. T. Chung, in *The Physics of Highly Charged Ions*, edited by M. Stockli and P. Richard, AIP Conf. Proc. No. 274 (AIP, New York, 1993)

23. W. R. Johnson, Z. W. Liu, and J. Sapirstein, ATOMIC DATA AND NUCLEAR DATA TABLES **64,** 279 (1996)

24. A. Schmitt, U. Volz, and H. Schmoranzer, in *Proceedings of the International Conference on Atomic and Molecular Data and Their Application (ICAMDATA),* Gaithersburg, MD, 1997, edited by P. J. Mohr and W. L. Wiese, Natl. Inst. Stand. Technol., Spec. Publ. (U.S. Government Printing Office, Washington, DC, 1998)

EXPLANATION OF TABLES

TABLE I. Energy Levels and Lifetimes for Li-like Ions, $Z = 3$ to $Z = 8$

Configuration	Label designating the level.
Term	^2L.
J	J-value of the level.
Total Energy	Computed total energy in atomic units (in a.u.).
Energy Levels	Energy (cm^{-1}) of the level relative to the ground state; includes the normal mass shift.
Splitting	Fine-structure splitting of levels of a term (in cm^{-1}).
Lifetimes	Lifetimes of the levels (in s).

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

Multiplet	Lower and upper term for the transition.
J_i, J_k	J-value of lower and upper term.
E	Transition energy (E(upper) − E(lower)) in cm^{-1}; includes the normal mass shift.
S	Line strength for the transition (in length form in a.u.).
gf	Weighted oscillator strength.
A_{ki}	Transition or decay rate for the line, in emission; the notation 6.27836E+02 denotes 6.27836×10^2.

TABLE I. Energy Levels and Lifetimes for Li-like Ions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Neutral Li ($Z = 3$). The Rydberg Constant Used Is 109728.71422.

Configuration	Term	J	Total Energy (a.u.)	Energy Levels (cm^{-1})	Splitting (cm^{-1})	Lifetimes (s)
$1s^2 2s$	^2S	1/2	−7.478567258			
$1s^2 2p$	$^2P^o$	1/2	−7.410653818	14904.1089		2.7103E−08
		3/2	−7.410652299	14904.4423	.3334	2.7101E−08
$1s^2 3s$	^2S	1/2	−7.354607139	27203.9689		2.9886E−08
$1s^2 3p$	$^2P^o$	1/2	−7.337655972	30924.0285		2.1094E−07
		3/2	−7.337655536	30924.1241	.0957	2.1093E−07
$1s^2 3d$	^2D	3/2	−7.336031499	31280.5311		1.4591E−08
		5/2	−7.336031335	31280.5671	.0360	1.4592E−08
$1s^2 4s$	^2S	1/2	−7.319040979	35009.2270		5.6084E−08

Li-like ^{9}Be ($Z = 4$). The Rydberg Constant Used Is 109730.62689.

Configuration	Term	J	Total Energy (a.u.)	Energy Levels (cm^{-1})	Splitting (cm^{-1})	Lifetimes (s)
$1s^2 2s$	^2S	1/2	−14.326947328			
$1s^2 2p$	$^2P^o$	1/2	−14.181444345	31932.2671		8.8528E−09
		3/2	−14.181414480	31938.8213	6.5542	8.8471E−09
$1s^2 3s$	^2S	1/2	−13.924915329	88230.4466		2.4497E−09
$1s^2 3p$	$^2P^o$	1/2	−13.887258264	96494.7133		5.4181E−09
		3/2	−13.887249479	96496.6412	1.9280	5.4159E−09
$1s^2 3d$	^2D	3/2	−13.880159533	98052.6097		9.0436E−10
		5/2	−13.880156909	98053.1855	.5759	9.0450E−10
$1s^2 4s$	^2S	1/2	−13.800834180	115461.4511		4.1315E−09

Li-like ^{11}B ($Z = 5$). The Rydberg Constant Used Is 109731.84175.

Configuration	Term	J	Total Energy (a.u.)	Energy Levels (cm^{-1})	Splitting (cm^{-1})	Lifetimes (s)
$1s^2 2s$	^2S	1/2	−23.430762555			
$1s^2 2p$	$^2P^o$	1/2	−23.210372514	48367.6102		5.2891E−09
		3/2	−23.210217444	48401.6424	34.0322	5.2772E−09
$1s^2 3s$	^2S	1/2	−22.609654833	180203.3252		6.2037E−10
$1s^2 3p$	$^2P^o$	1/2	−22.551561739	192952.6496		7.7478E−10
		3/2	−22.551515968	192962.6947	10.0451	7.7320E−10
$1s^2 3d$	^2D	3/2	−22.537366939	196067.8927		1.7952E−10
		5/2	−22.537353665	196070.8059	2.9132	1.7958E−10
$1s^2 4s$	^2S	1/2	−22.347687692	237695.5989		1.0134E−09

TABLE I. Energy Levels and Lifetimes for Li-like Ions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Li-like ^{12}C ($Z = 6$). The Rydberg Constant Used Is 109732.29786.

Configuration	Term	J	Total Energy (a.u.)	Energy Levels (cm^{-1})	Splitting (cm^{-1})	Lifetimes (s)
$1s^2 2s$	^2S	1/2	−34.789478176			
$1s^2 2p$	$^2P^o$	1/2	−34.495566501	64503.2069		3.7993E−09
		3/2	−34.495078565	64610.2916	107.0847	3.7794E−09
$1s^2 3s$	^2S	1/2	−33.409477131	302861.3714		2.3500E−10
$1s^2 3p$	$^2P^o$	1/2	−33.331103633	320061.5795		2.1425E−10
		3/2	−33.330959968	320093.1089	31.5294	2.1450E−10
$1s^2 3d$	^2D	3/2	−33.309137612	324882.3434		5.7164E−11
		5/2	−33.309095665	324891.5493	9.2059	5.7196E−11
$1s^2 4s$	^2S	1/2	−32.960700059	401352.0501		3.7471E−10

Li-like ^{14}N ($Z = 7$). The Rydberg Constant Used Is 109733.01461.

Configuration	Term	J	Total Energy (a.u.)	Energy Levels (cm^{-1})	Splitting (cm^{-1})	Lifetimes (s)
$1s^2 2s$	^2S	1/2	−48.404528237			
$1s^2 2p$	$^2P^o$	1/2	−48.037727909	80500.2115		2.9741E−09
		3/2	−48.036548140	80759.1307	258.9192	2.9442E−09
$1s^2 3s$	^2S	1/2	−46.326003831	456165.4980		1.0985E−10
$1s^2 3p$	$^2P^o$	1/2	−46.227461096	477792.2808		8.1328E−11
		3/2	−46.227118106	477867.5554	75.2747	8.2058E−11
$1s^2 3d$	^2D	3/2	−46.197320898	484407.0304		2.3547E−11
		5/2	−46.197218468	484429.5103	22.4799	2.3566E−11
$1s^2 4s$	^2S	1/2	−45.641625288	606363.3394		1.7212E−10

Li-like ^{16}O ($Z = 8$). The Rydberg Constant Used Is 109733.55219.

Configuration	Term	J	Total Energy (a.u.)	Energy Levels (cm^{-1})	Splitting (cm^{-1})	Lifetimes (s)
$1s^2 2s$	^2S	1/2	−64.278217625			
$1s^2 2p$	$^2P^o$	1/2	−63.838784972	96441.0119		2.4460E−09
		3/2	−63.836362003	96972.7739	531.7620	2.4043E−09
$1s^2 3s$	^2S	1/2	−61.361486792	640126.4701		5.8546E−11
$1s^2 3p$	$^2P^o$	1/2	−61.242822406	666169.3993		3.7854E−11
		3/2	−61.242115826	666324.4704	155.0711	3.8114E−11
$1s^2 3d$	^2D	3/2	−61.204258745	674632.8543		1.1409E−11
		5/2	−61.204046279	674679.4836	46.6293	1.1423E−11
$1s^2 4s$	^2S	1/2	−60.392729454	852736.8380		9.0623E−11

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Neutral ^{7}Li ($Z = 3$)

Multiplet J_i - J_k	$E(\mathrm{cm}^{-1})$	S	gf	A_{ki}
$1s^2 3p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	356.41	27.3779	.02964	6.27836E+02
3/2 - 5/2	356.44	246.4010	.26678	3.76816E+03
1/2 - 3/2	356.50	136.8890	.14824	3.14170E+03
$1s^2 3s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	3720.06	71.6942	.81014	3.73913E+06
1/2 - 3/2	3720.16	143.3890	1.62032	3.73942E+06
$1s^2 3p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	4085.10	71.9351	.89262	4.96805E+06
1/2 - 1/2	4085.20	35.9674	.44632	2.48419E+06
$1s^2 2p\ ^2P^o - 1s^2 3s\ ^2S$				
3/2 - 1/2	12299.53	11.8339	.44212	2.23064E+07
1/2 - 1/2	12299.86	5.9169	.22106	1.11540E+07
$1s^2 2s\ ^2S - 1s^2 2p\ ^2P^o$				
1/2 - 1/2	14904.11	11.0008	.49803	3.68960E+07
1/2 - 3/2	14904.44	22.0017	.99608	3.68986E+07
$1s^2 2p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	16376.09	5.1343	.25540	1.14214E+07
3/2 - 5/2	16376.12	46.2086	2.29857	6.85286E+07
1/2 - 3/2	16376.42	25.6713	1.27700	5.71099E+07
$1s^2 2p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	20104.78	.8404	.05132	6.91877E+06
1/2 - 1/2	20105.12	.4202	.02566	3.45952E+06
$1s^2 2s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	30924.03	.0334	.00314	1.00146E+06
1/2 - 3/2	30924.12	.0669	.00628	1.00152E+06

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Li-like ^{9}Be ($Z = 4$)

Multiplet J_i - J_k	$E(\mathrm{cm}^{-1})$	S	gf	A_{ki}
$1s^2 3p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	1555.97	6.8515	.03238	1.30737E+04
3/2 - 5/2	1556.54	61.6639	.29155	7.85292E+04
1/2 - 3/2	1557.90	34.2555	.16210	6.56075E+04
$1s^2 3s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	8264.27	22.0452	.55340	1.26056E+07
1/2 - 3/2	8266.19	44.0924	1.10712	1.26150E+07
$1s^2 3p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	18964.81	9.3545	.53888	6.46400E+07
1/2 - 1/2	18966.74	4.6769	.26945	3.23276E+07
$1s^2 2s\ ^2S - 1s^2 2p\ ^2P^o$				
1/2 - 1/2	31932.27	3.4244	.33216	1.12958E+08
1/2 - 3/2	31938.82	6.8492	.66448	1.13032E+08
$1s^2 2p\ ^2P^o - 1s^2 3s\ ^2S$				
3/2 - 1/2	56291.62	1.5059	.25749	2.72123E+08
1/2 - 1/2	56298.18	.7529	.12874	1.36091E+08
$1s^2 2p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	66113.79	1.2587	.25277	1.84245E+08
3/2 - 5/2	66114.36	11.3280	2.27497	1.10550E+09
1/2 - 3/2	66120.34	6.2929	1.26389	9.21427E+08
$1s^2 2p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	83522.63	.1638	.04157	9.67128E+07
1/2 - 1/2	83529.18	.0819	.02078	4.83602E+07
$1s^2 2s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	96494.71	.1889	.05537	1.71960E+08
1/2 - 3/2	96496.64	.3780	.11079	1.72025E+08

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Li-like ^{11}B ($Z = 5$)

Multiplet J_i - J_k	$E(\mathrm{cm}^{-1})$	S	gf	A_{ki}
$1s^2 3p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	3105.20	3.0412	.02869	4.61231E+04
3/2 - 5/2	3108.11	27.3710	.25841	2.77521E+05
1/2 - 3/2	3115.24	15.1990	.14382	2.32754E+05
$1s^2 3s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	12749.32	10.4893	.40622	2.20214E+07
1/2 - 3/2	12759.37	20.9851	.81333	2.20804E+07
$1s^2 3p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	44732.90	2.9131	.39582	2.64159E+08
1/2 - 1/2	44742.95	1.4558	.19785	1.32100E+08
$1s^2 2s\ ^2S - 1s^2 2p\ ^2P^o$				
1/2 - 1/2	48367.61	1.6494	.24233	1.89069E+08
1/2 - 3/2	48401.64	3.2992	.48506	1.89494E+08
$1s^2 2p\ ^2P^o - 1s^2 3s\ ^2S$				
3/2 - 1/2	131801.68	.4632	.18546	1.07450E+09
1/2 - 1/2	131835.71	.2315	.09271	5.37436E+08
$1s^2 2p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	147666.25	.5690	.25521	9.27990E+08
3/2 - 5/2	147669.16	5.1207	2.29691	5.56821E+09
1/2 - 3/2	147700.28	2.8442	1.27605	4.64209E+09
$1s^2 2p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	189293.95	.0573	.03294	3.93684E+08
1/2 - 1/2	189327.99	.0286	.01647	1.96847E+08
$1s^2 2s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	192952.65	.1743	.10217	1.26867E+09
1/2 - 3/2	192962.69	.3493	.20474	1.27125E+09

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Li-like ^{12}C ($Z = 6$)

Multiplet J_i - J_k	$E(\mathrm{cm}^{-1})$	S	gf	A_{ki}
$1s^2 3p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	4789.23	1.7086	.02486	9.50678E+04
3/2 - 5/2	4798.44	15.3771	.22413	5.73708E+05
1/2 - 3/2	4820.76	8.5441	.12511	4.84865E+05
$1s^2 3s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	17200.21	6.1054	.31899	3.14740E+07
1/2 - 3/2	17231.74	12.2111	.63916	3.16483E+07
$1s^2 2s\ ^2S - 1s^2 2p\ ^2P^o$				
1/2 - 1/2	64503.21	.9681	.18968	2.63205E+08
1/2 - 3/2	64610.29	1.9367	.38009	2.64592E+08
$1s^2 3p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	81258.94	1.3140	.32434	7.14253E+08
1/2 - 1/2	81290.47	.6568	.16218	3.57432E+08
$1s^2 2p\ ^2P^o - 1s^2 3s\ ^2S$				
3/2 - 1/2	238251.08	.2070	.14983	2.83646E+09
1/2 - 1/2	238358.16	.1034	.07488	1.41884E+09
$1s^2 2p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	260272.05	.3262	.25792	2.91360E+09
3/2 - 5/2	260281.25	2.9361	2.32137	1.74832E+10
1/2 - 3/2	260379.13	1.6305	1.28956	1.45793E+10
$1s^2 2s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	320061.57	.1396	.13569	4.63587E+09
1/2 - 3/2	320093.10	.2787	.27101	4.63043E+09
$1s^2 2p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	336741.75	.0275	.02815	1.06474E+09
1/2 - 1/2	336848.84	.0137	.01407	5.32290E+08

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Li-like ^{14}N ($Z = 7$)

Multiplet J_i - J_k	$E(\mathrm{cm}^{-1})$	S	gf	A_{ki}
$1s^2 3p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	6539.47	1.0929	.02171	1.54818E+05
3/2 - 5/2	6561.95	9.8365	.19606	9.38543E+05
1/2 - 3/2	6614.75	5.4788	.11008	8.03221E+05
$1s^2 3s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	21626.78	3.9952	.26246	4.09408E+07
1/2 - 3/2	21702.06	7.9781	.52593	4.13056E+07
$1s^2 2s\ ^2S - 1s^2 2p\ ^2P^o$				
1/2 - 1/2	80500.21	.6362	.15557	3.36234E+08
1/2 - 3/2	80759.13	1.2731	.31229	3.39648E+08
$1s^2 3p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	128495.78	.7238	.28252	1.55573E+09
1/2 - 1/2	128571.06	.3630	.14177	7.81568E+08
$1s^2 2p\ ^2P^o - 1s^2 3s\ ^2S$				
3/2 - 1/2	375406.36	.1132	.12910	6.06792E+09
1/2 - 1/2	375665.28	.0565	.06449	3.03536E+09
$1s^2 2p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	403647.89	.2123	.26025	7.07107E+09
3/2 - 5/2	403670.37	1.9103	2.34235	4.24323E+10
1/2 - 3/2	403906.81	1.0605	1.30112	3.53967E+10
$1s^2 2s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	477792.27	.1109	.16096	1.22550E+10
1/2 - 3/2	477867.55	.2197	.31894	1.21452E+10
$1s^2 2p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	525604.20	.0157	.02513	2.31541E+09
1/2 - 1/2	525863.12	.0079	.01255	1.15719E+09

TABLE II. Line Strengths, Weighted Oscillator Strengths, and Decay Rates for E1 Transitions, $Z = 3$ to $Z = 8$

See page 126 for Explanation of Tables

Li-like ^{16}O ($Z = 8$)

Multiplet J_i - J_k	$E(\mathrm{cm}^{-1})$	S	gf	A_{ki}
$1s^2 3p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	8308.38	.7580	.01913	2.20217E+05
3/2 - 5/2	8355.01	6.8227	.17315	1.34373E+06
1/2 - 3/2	8463.45	3.7983	.09765	1.16639E+06
$1s^2 3s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	26042.93	2.8106	.22234	5.02929E+07
1/2 - 3/2	26198.00	5.6144	.44678	5.11348E+07
$1s^2 2s\ ^2S - 1s^2 2p\ ^2P^o$				
1/2 - 1/2	96441.01	.4499	.13180	4.08832E+08
1/2 - 3/2	96972.77	.9005	.26524	4.15928E+08
$1s^2 3p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	186412.36	.4502	.25494	2.95464E+09
1/2 - 1/2	186567.44	.2257	.12789	1.48465E+09
$1s^2 2p\ ^2P^o - 1s^2 3s\ ^2S$				
3/2 - 1/2	543153.69	.0701	.11572	1.13855E+10
1/2 - 1/2	543685.45	.0350	.05777	5.69523E+09
$1s^2 2p\ ^2P^o - 1s^2 3d\ ^2D$				
3/2 - 3/2	577660.07	.1494	.26216	1.45879E+10
3/2 - 5/2	577706.70	1.3446	2.35952	8.75446E+10
1/2 - 3/2	578191.83	.7462	1.31053	7.30592E+10
$1s^2 2s\ ^2S - 1s^2 3p\ ^2P^o$				
1/2 - 1/2	666169.39	.0880	.17815	2.63673E+10
1/2 - 3/2	666324.46	.1747	.35368	2.61857E+10
$1s^2 2p\ ^2P^o - 1s^2 4s\ ^2S$				
3/2 - 1/2	755764.05	.0101	.02309	4.39824E+09
1/2 - 1/2	756295.81	.0050	.01152	2.19721E+09